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Precise Navigation Over Wide Areas Using Satellites

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Advanced Orbital Systems Directorate

69 AUG 06

Satellite Systems Division
AEROSPACE CORPORATION

Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

THE AEROSPACE CORPORATION

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Satellite Systems Division
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El Segundo, California

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-69-C-0066. The report was authored by J. B. Woodford of the Advance Orbital Systems Directorate and P. W. Soule of the Satellite Systems Division.

This report, which documents research carried out from January through March 1969, was submitted on 5 June 1969 to Lt Col F. Charette, SMAOO, for review and approval.

Approved

P M Diamond

P. M. Diamond
Associate General Manager
Office for Development Planning

This technical report has been reviewed and is approved.

Franklin M. Charette

Franklin M. Charette, Lt Col, USAF
Chief, Orbital Systems Branch
Space and Missile Systems Organization

ABSTRACT

A class of satellite-based radio navigation systems is described which can offer precise, near global position fixing capability to a wide variety of users. The system operation, based on one-way pseudo-ranging by a user to four satellites in 24-hour inclined, elliptical orbits, is described. Ground coverage and the factors influencing accura are discussed.

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INTRODUCTION

Man has always needed to navigate. Improvements in the technology of transportation have stimulated, or have been stimulated by, improvements in the technology of navigation. As his intrinsic mobility has been extended by ships, wheeled vehicles, aircraft, and now even space vehicles, so has his need for navigation grown in the size of region of coverage, accuracy, and time availability. So perhaps it is not surprising that recently developed space technology can be exploited to provide exciting new navigation capabilities. The purpose here is to describe an approach to a navigation system which, with available technology, can provide three-component position determination in geodetic coordinates virtually instantaneously anywhere on or near the earth to accuracies measured in tens of feet.

PROPERTIES OF SATELLITE SYSTEMS FOR NAVIGATION

The unique geometry of a satellite relative to the earth allows visibility of the satellite over wide areas. One satellite at synchronous altitude can be observed over approximately one-third of the surface of the earth. This characteristic provides two important attributes to a navigation system that uses satellites. The first is that wide (or global) coverage can be obtained in an economically feasible manner. Figure 1 depicts the earth as viewed from a satellite in stationary synchronous orbit. The practical coverage is somewhat less than the apparent disk from synchronous altitudes because of the receiver elevation angle constraint. The second advantage is that line-of-sight radio frequency (RF) propagation can be employed over the entire coverage area with the attendant advantages that uncomplicated and precise range (or range rate) determinations can be made. Frequencies on the order of 0.1 to 15 GHz propagate well through the ionosphere and atmosphere and the available bandwidth at these frequencies further enhances the ability to make precise and unambiguous measurements. By comparison, wide-coverage earth-based navigation systems are constrained to ground-wave propagation and hence frequencies below

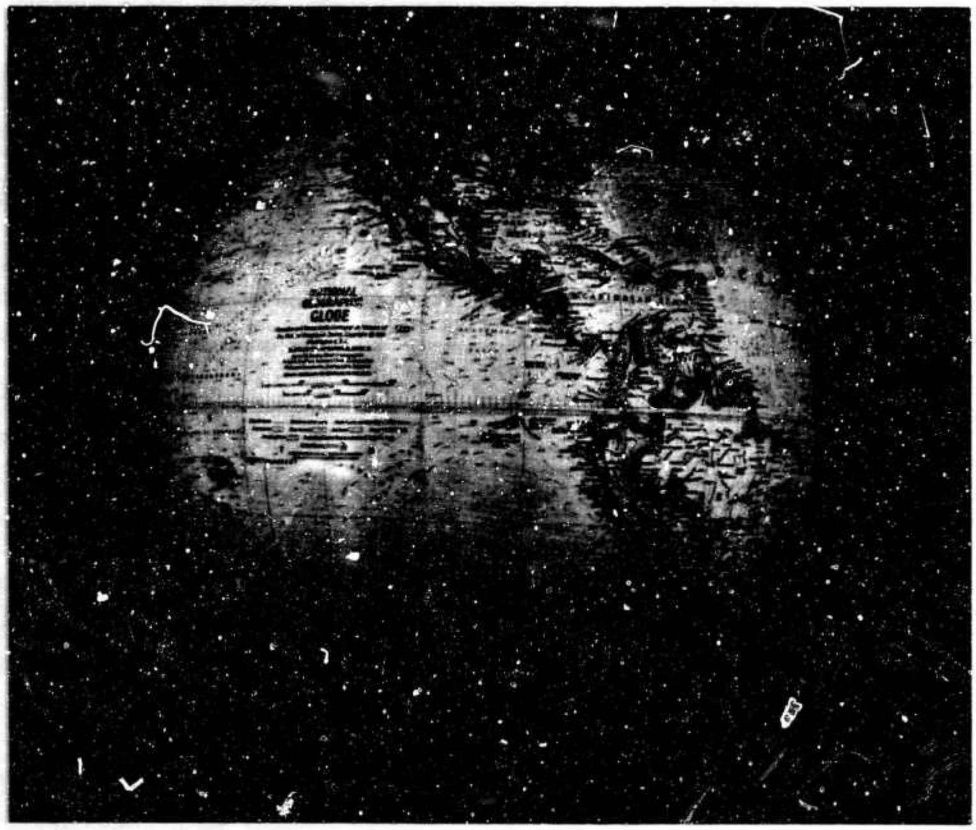

Fig. 1. Depiction of the Earth as Viewed from Synchronous Altitude

100 to 200 kHz. Ground wave propagation at these low frequencies experiences large and unpredictable (though often repeatable) delays.

Unfortunately, satellites are not themselves bench marks in the sense that they can be set at a fixed position in earth coordinates. However, satellite tracking accuracy has improved to the point where the contribution to navigation error due to satellite position uncertainty is no longer a limiting factor.

Disadvantages of satellites for navigation are associated with the high cost of establishing and maintaining the system in orbit and the limitation on the electrical power that can be generated. Satellite RF power generation will be limited to several hundreds of watts for the next few years. Thus, the signal strength received with an earth coverage satellite broadcast will be quite low and user equipment must be able to use it efficiently. The properties of satellites for navigation systems are summarized in Table 1.

Table 1. Properties of Satellites for Navigation

Advantages

- Wide Coverage
- Line-of-sight Radio Frequencies
  - Relatively Free From Anomalies
  - Wide Bandwidth Available

Problems to be Overcome

- Not Fixed in Earth Coordinates
- Relatively Costly
- Low Radiated Power

PROPERTIES OF POTENTIAL USERS

A prerequisite to support the relatively high cost of deploying a satellite system for navigation is to design a configuration which is attractive to many potential users. The majority of these users will be those to whom the advantages offered by satellite systems have special appeal. The high accuracy and three-dimensional-fix capability, for example, is of special interest for geodesy, cartography, and topography. Continuous position fixing over wide areas is important for moving vehicles such as satellites, aircraft, and ships. For these applications the equipment must be small and portable, the antennas required must be simple, and the accuracy must not be significantly affected by rapid motion of the user.

A series of features and summary performance criteria for a desirable navigation system are outlined in Table 2. The desired features of no radiation from the user and no system saturation are inherent properties of the passive class of systems. These requirements may be of more interest in potential military application than in civilian application.

Table 2. Desirable Features for a Navigation System

Global Coverage
Continuous Availability
Three Dimension Position and Velocity Fix
Real Time Measurements
Accuracy to a Few Tens of Feet
Usable on Rapidly Maneuvering Vehicles
No Radiation from User - No System Saturation
Adaptable to Many Classes of Users
Available with Present Technology

SYSTEM CONSIDERATIONS

A variety of navigation systems using satellites can be configured. These systems will vary in coverage, accuracy, availability, and cost. This report is limited to consideration of systems with wide coverage and high accuracy. This section is devoted to describing the considerations which lead to the selection of the system which has been found to best meet these aims. Analysis indicates that only systems based on measuring the ranges between satellites and the user or the range difference between links to pairs of satellites can meet the accuracy goals while being available to users in high-speed aircraft. Consequently, systems based primarily on range rate or angle measurements will not be considered here. Furthermore, the desire to accommodate high-speed users requires all of the measurements needed to establish a navigation fix to be made essentially simultaneously.

Measurement of range can be accomplished by timing the two-way transmission of a suitable signal originating at the user and repeated back to the user by the satellite or by comparing the time of arrival of a signal with a clock at the user synchronized to a clock at the satellite. The latter method is preferred since it eliminates radio transmission by the user and ensures a system which cannot be saturated as the number of users increases. To maintain clock

synchronization with any clock presently feasible for inclusion in the user's equipment one additional measurement must be made. Since a three-dimensional fix is required, signals from four satellites need to be received. By measuring the time of arrival of the four signals relative to the user's clock, three-position coordinates and a clock correction can thus be determined. If, in addition, the frequency shift is measured, the three-component velocity vector of the user can be found. Since a clock correction is calculated, the user effectively has an extremely accurate time standard which may be of ancillary usefulness.

Table 3 summarizes the main options available in designing a satellite-based precise navigation system of the character outlined in Table 2. The options selected as best meeting these requirements are checked. Considerations leading to the selection of a 24-hr altitude are discussed in the Orbit Selection section.

Table 3. System Concept Options

✓Range Measurements	✓User Passive
Range-Rate Measurements	User Active
Angle Measurements	
Sequential Measurements	Medium Altitude
✓Simultaneous Measurements	✓24-hr Altitude

A system using the measurement technique just described will be termed a one-way pseudo-ranging system. It is essentially identical (except for computational algorithm) to a hyperbolic system in which three range differences are measured to four satellites.

ONE-WAY PSEUDO-RANGING NAVIGATION SYSTEM OPERATION

The concept of a one-way pseudo-ranging navigation system is shown in Fig. 2. The system consists of four satellites in high earth orbits, one master ground tracking station, and a number of subordinate ground stations. Some of the potential uses for such a system are indicated and include tracking of low altitude satellites and reentry vehicles as well as a variety of air land, and sea operations. The user receives a signal from each satellite. A signal satellite to user link is illustrated in Fig. 3. The user, in this case an aircraft, receives a continuous signal. An attempt is made to show by black and white segments a random-like signal, perhaps phase modulated, upon the carrier. To the user, the signal appears arrayed in time as the received signal in the lower part of Fig. 3. The user with a crystal oscillator clock (that is a normal crystal oscillator driving a suitable set of counters) generates a replica of the transmitted signal and controls its relative time position by introducing delay or advancement between his clock and the signal generation. The signal is moved back and forth in time until it correlates with the incoming signal. The delay required to achieve this situation is the time measurement. Equation 1 defines the nature of such a time measurement.

$$T = R/C - \Delta \quad \text{or} \quad R = (T + \Delta)C \tag{1}$$

Where T is the time measurement, Δ is the lag of user clock, R is the range from satellite to user, and C is the velocity of light. The time measurement is a function of the time it takes light to travel from a satellite to the aircraft less the lag of the user clock relative to the clock in the satellite which controls the satellite signal.

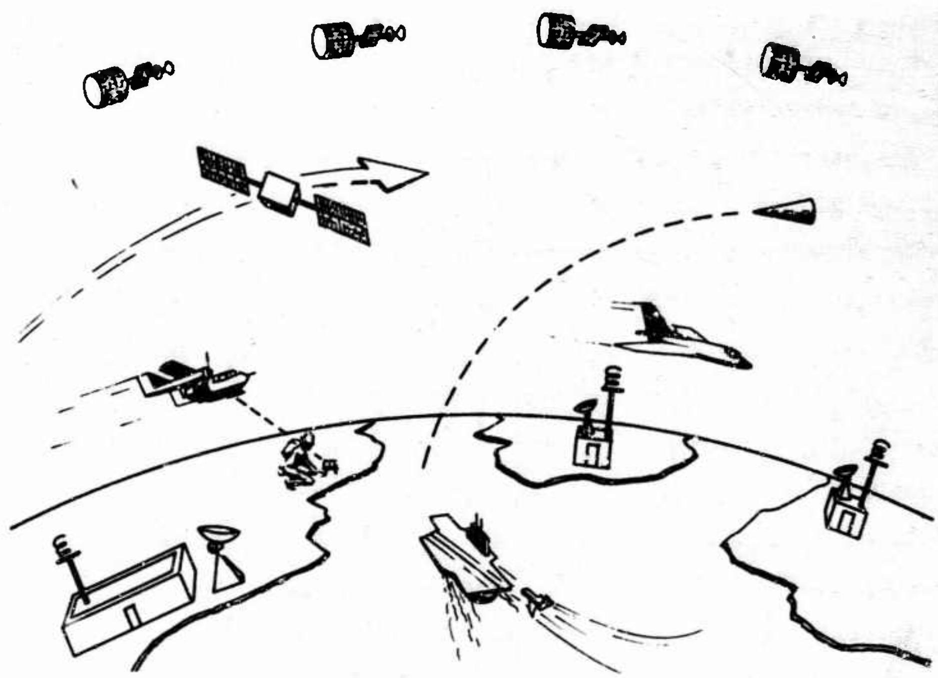

Fig. 2. System Configuration

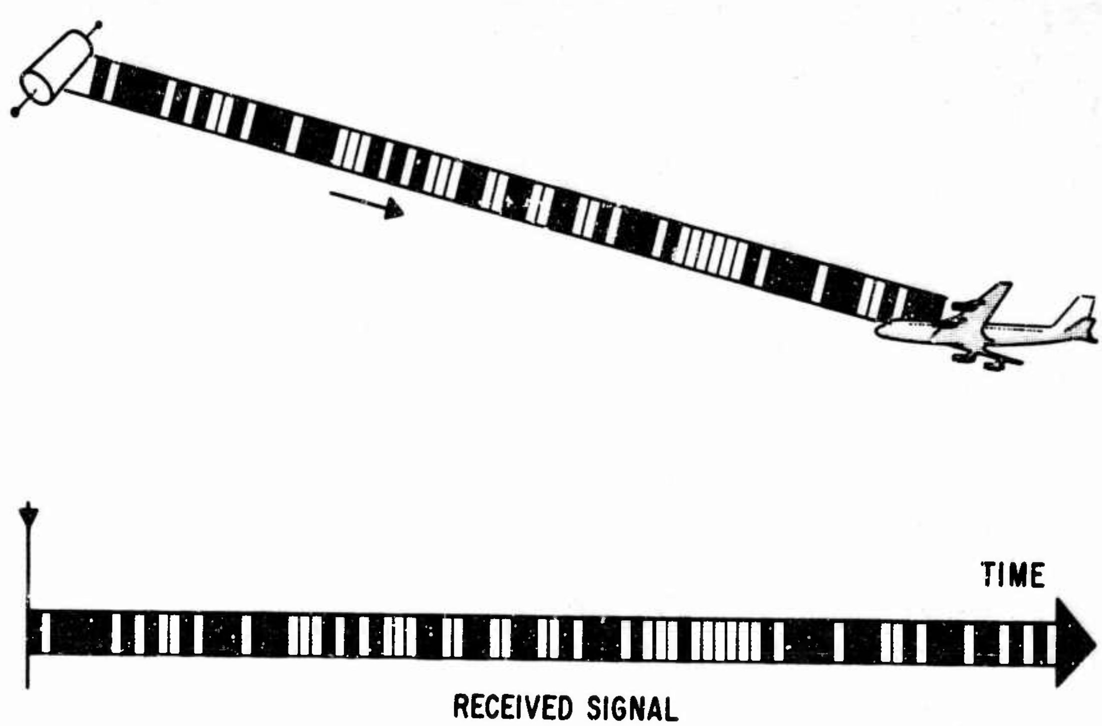

Fig. 3. Pseudo-Ranging to One Satellite

In Fig. 4 the pseudo-ranging from four satellites to a user is considered. For the purposes of this discussion, a Cartesian coordinate system is introduced. The origin of the coordinates can be taken as being the master tracking station. Assume that the satellite positions are known and that the satellite signals are synchronized by a process to be described later. Then measurements from satellites yield

$$T_j = R_j/C - \Delta \tag{2}$$

where $j = 1,2,3,4$. Since the satellite signals are synchronized and compared with the same user clock, the term "Δ" is the same for each measurement. The R's in the equations can be replaced with the expression in Cartesian coordinates for the distance between the satellite and the user.

$$T_j = 1/C \sqrt{(X_j - X)^2 + (Y_j - Y)^2 + (Z_j - Z)^2} - \Delta \tag{3}$$

There are four equations in four unknowns; where X_j = X coordinate of jth satellite and X = X coordinate of the user. There is sufficient information, if the geometry of the satellites yields a definite solution, to solve for the user's position in three coordinates and a clock correction. Incidently, if the doppler of each of the incoming signals is measured, a similar solution can be achieved for the velocity in three components and a clock frequency.

The previous discussion indicates the principle upon which measurements made on signals from four satellites can yield position, velocity, time, and frequency for a user. It remains to be shown that there exists methods by which the satellites can be accurately tracked for its position and the clocks on the satellite can be accurately synchronized. Figure 5 shows the first step in a multi-step tracking and synchronization sequence. The master ground station with a tracking antenna sequentially ranges to each of the satellites using two-way time measurements. A sequence of these measurements together with earth models and the laws of satellite motion allows estimates of the satellite position with fair accuracy. At this point, the round trip times

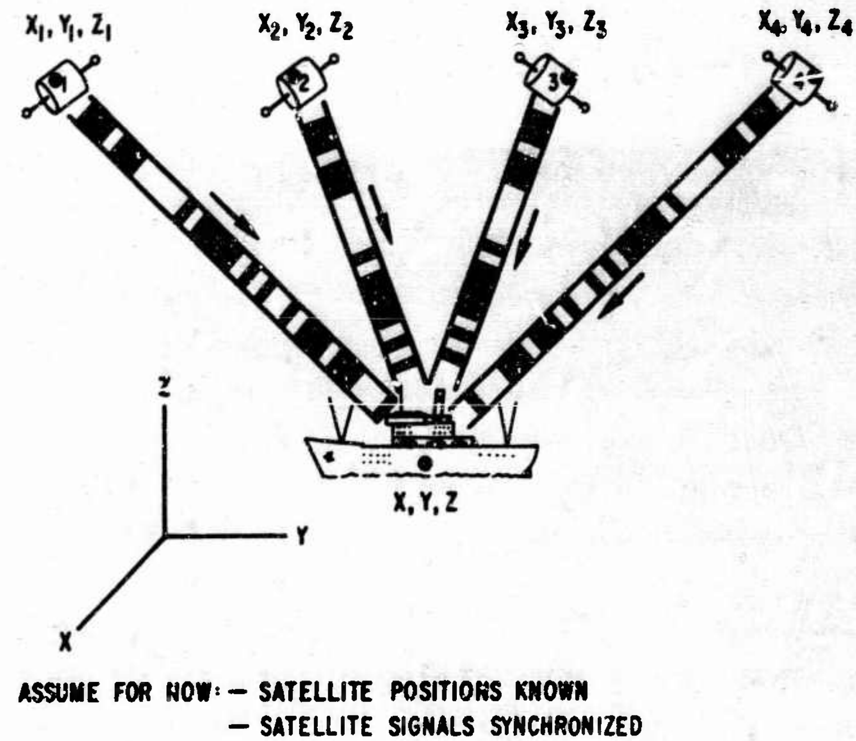

Fig. 4. Pseudo-Ranging to Four Satellites

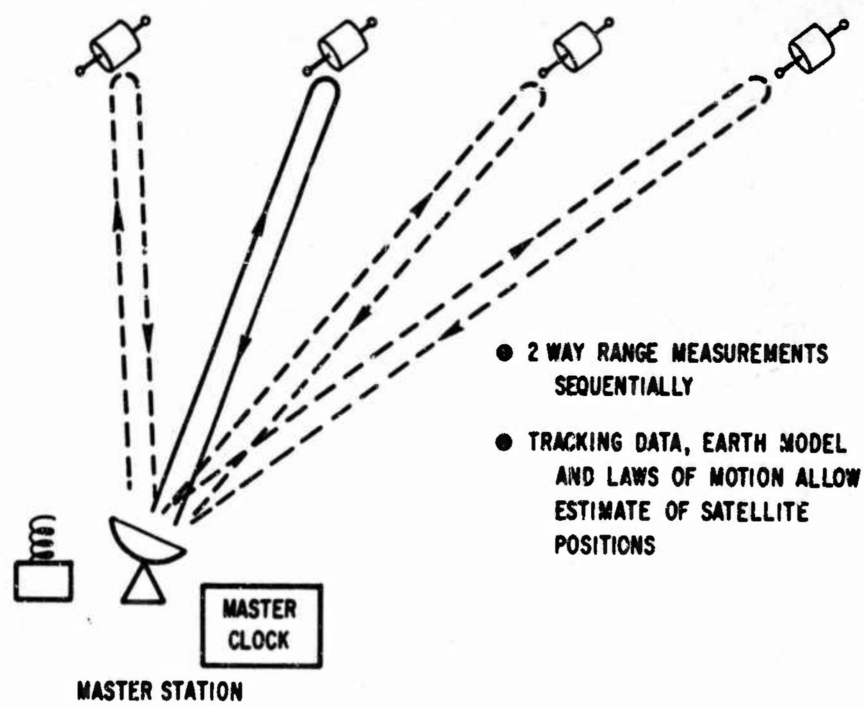

Fig. 5. Tracking and Synchronization - Step I

and hence the one-way times for the signal to propagate between the master station and each satellite are known. The master station, by receiving the navigation signal from each satellite as in Fig. 6, can compare the timing of these signals by using the accurately measured time of travel between each satellite and the master station. This process determines whether the satellite clock is running fast, slow, or on time relative to a master station clock. Signal synchronization can now be achieved either by altering the setting of the clock through a command link or by a correction transmitted to the user.

The clock now is synchronized, but the satellite positions are not known sufficiently well to allow the desired navigation accuracy. A solution to this problem could be the installation of additional master stations to perform satellite tracking from other locations and use range trilateration to refine the estimate of satellite position. On the other hand, less elaborate equipment

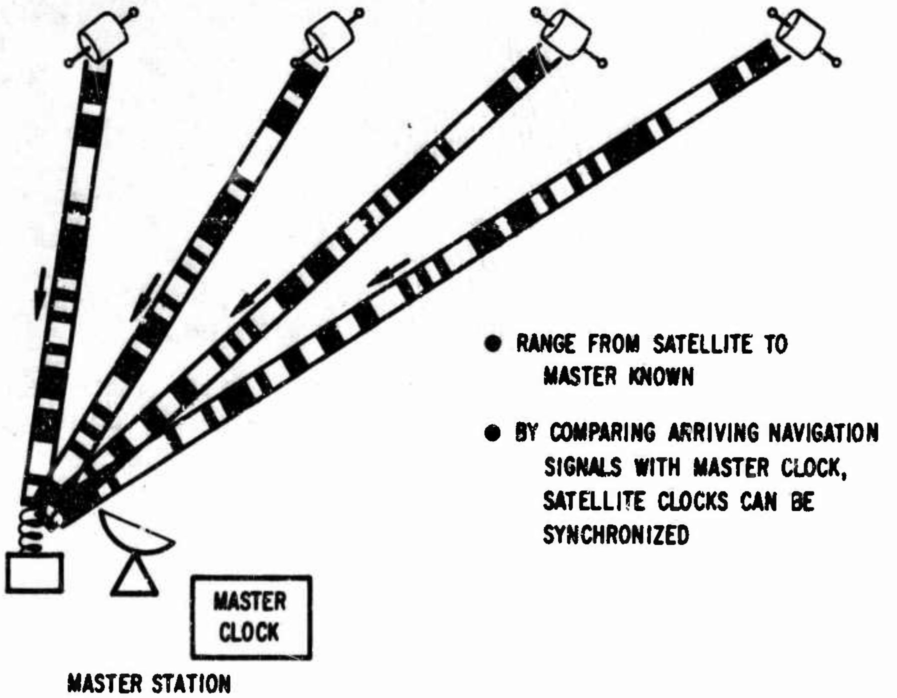

Fig. 6. Tracking and Synchronization - Step II

could be used to perform the same function as indicated in Fig. 7. Two or more auxiliary stations are located at known positions and receive the navigation signal from each satellite. Time of arrival measurements relative to local crystal oscillators are made on each signal and the data, as shown in Fig. 8, is relayed back to the master station through a low data rate link using one or more of the satellites. The master station is able to compute an apparent location for the master ground station and each auxiliary station using the same computational procedure as would a normal user, and the estimated satellite positions determined in Fig. 5. The steps in this procedure are indicated in Table 4. The estimated satellite positions can now be adjusted in order to force the apparent station locations to coincide with the surveyed location, a process which drives the navigational error to close to zero at each station location. Control of navigation error over the entire system coverage area is obtained with this system calibration technique due to the high correlation of the errors made at the auxilliary station and the navigator's location, even though they may be separated by many hundreds of miles. In the process, corrections are made for second order ionospheric uncertainties, one of the major error sources.

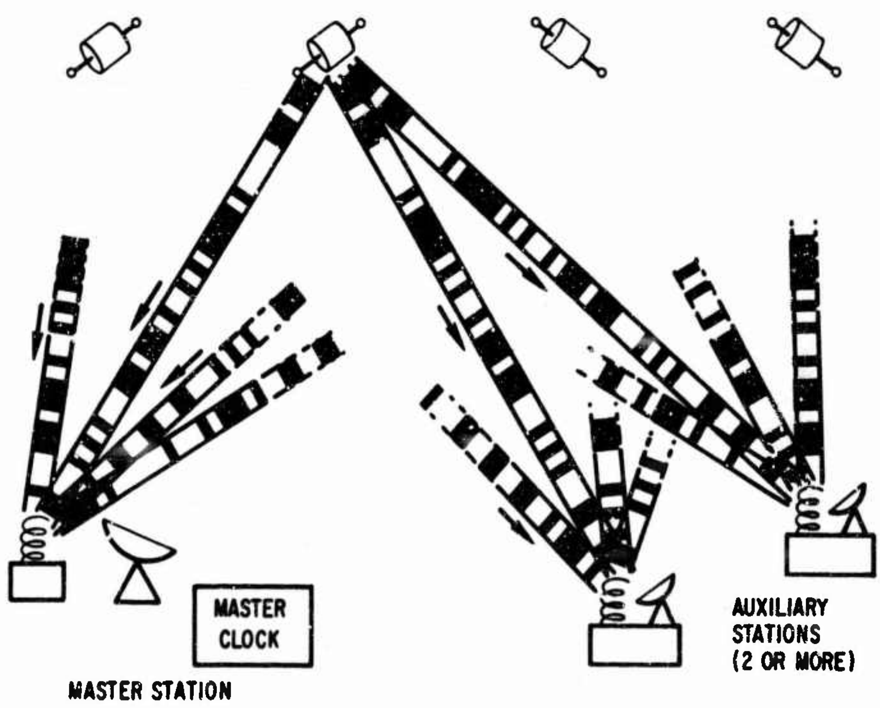

Fig. 7. Tracking and Synchronization - Step III

ERROR SOURCES

A primary objective of the system just described is the achievement of high navigational accuracy. In considering the accuracy of this system, a detailed description of individual error sources must be made. Table 5 is a summary of error sources that were considered. It is considerably beyond the scope of this report to describe the nature of the individual contributions. However, the system concept which has just been described can be configured to have an error performance consistent with the criteria in Table 2. Of all the errors listed, only the contribution of ionospheric uncertainties is not subject to unlimited control by the system designer. The primary consideration in assessing the effect of this source of error on a user remote from the master and auxiliary ground stations is the correlation of the ionospheric errors over the four paths to the user. The effect of this correlation is indicated in Fig. 9 where the resulting position error is given as a function

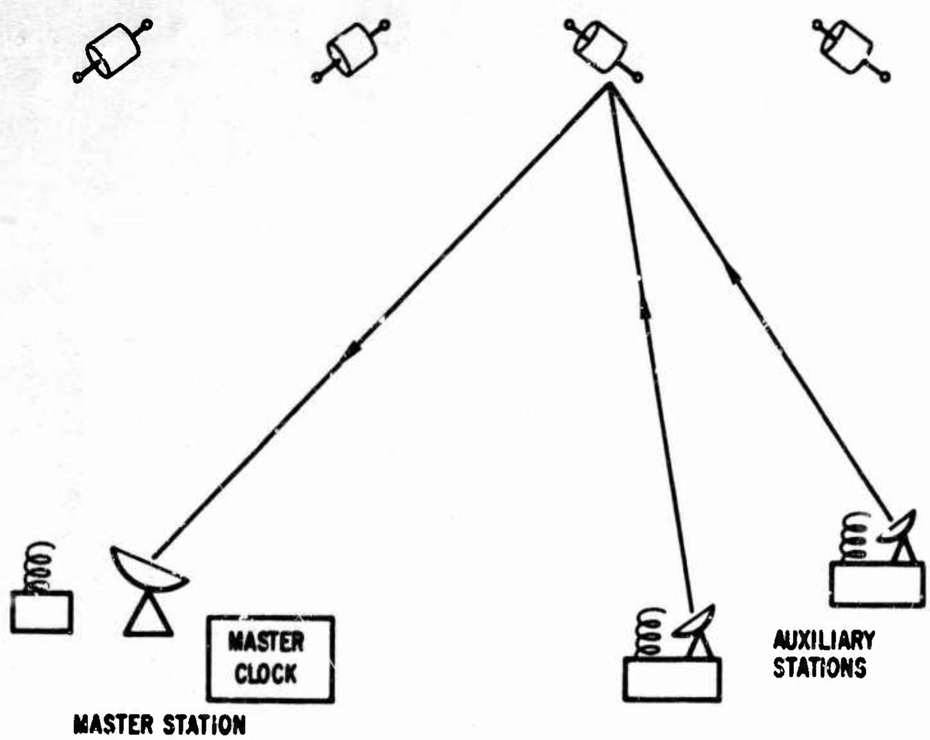

Fig. 8. Tracking and Synchronization - Step IV (Return of Data to the Master Station)

Table 4. Tracking and Synchronization - Step V
(System Calibration)

Master Station Computes Apparent Location of Each Station Using Estimated Satellite Positions

Estimated Satellite Positions Adjusted to Force Apparent Station Locations to Coincide with Surveyed Locations

This Process Also Corrects for Second Order Ionospheric Uncertainties

Table 5. Contributions to System Error Considered

Satellite Tracking Errors

- Station Location
- Range Measurement
- Earth Model
- Satellite Clock Drift
- Auxiliary Station Clock Drift

Range Measurement Errors

- Multipath
- Ionospheric Uncertainties
- Tropospheric Uncertainties
- Receiver Noise
- Receiver Precision

Geometric Dilution of Precision

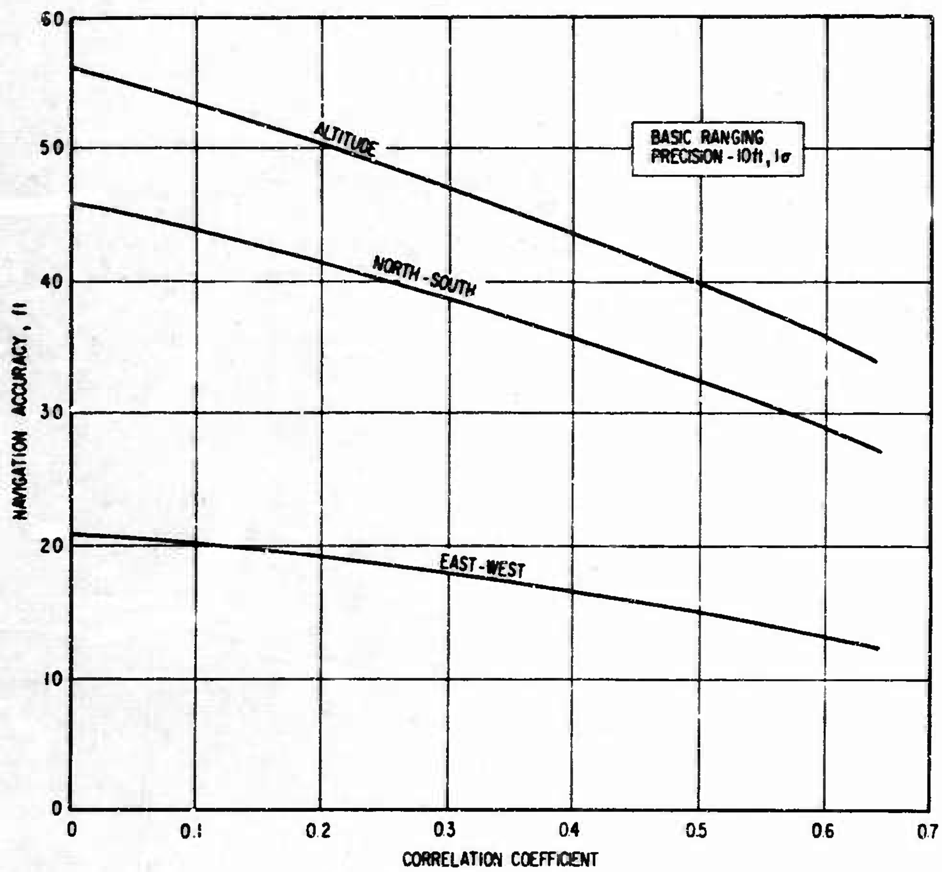

Fig. 9. Effect of Measurement Error Correlation

of the correlation coefficient for an assumed precision of range measurement of 10 ft, 1σ.

ORBIT SELECTION

Synchronous orbits (not necessarily circular or equatorial) are preferred from the standpoint of providing good coverage and the ability to deploy less than a full global system. A particularly attractive configuration employs one satellite in a synchronous, near circular, equatorial orbit in conjunction with three or four satellites in inclined, elliptical, carefully phased orbits, having the property that their ground traces follow a common near-circular path

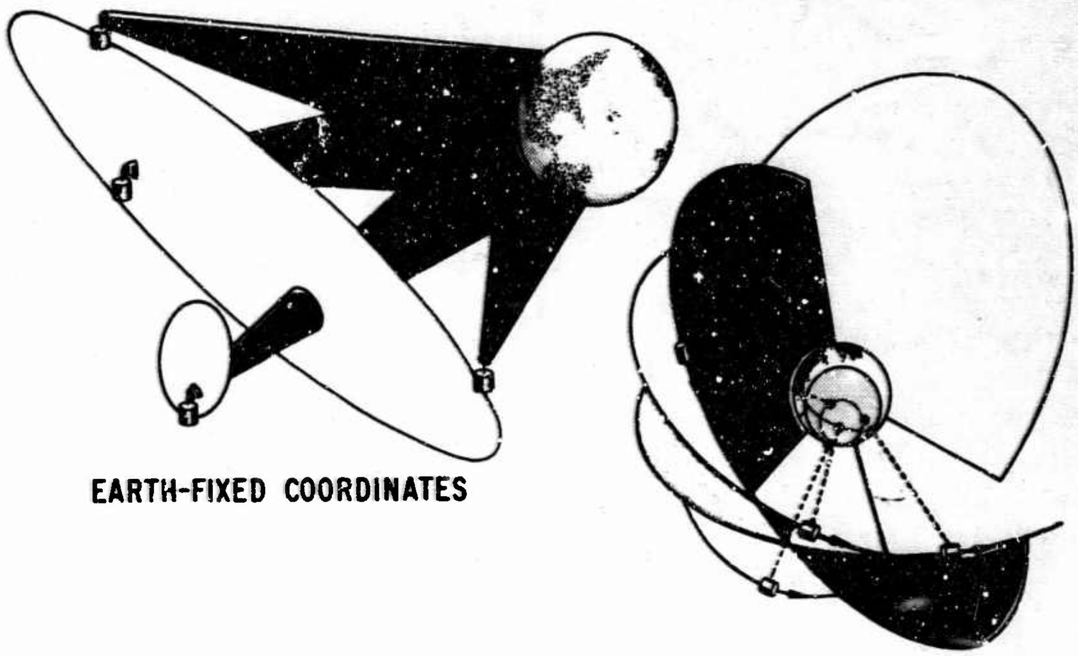

Fig. 10. Orbital Deployment - Two Views

around the trace of the first satellite. Such a constellation provides excellent coverage of the earth with a nearly ideal geometry for providing accurate navigation. Three or four such constellations can provide nearly global coverage. The satellite configuration which has just been described is shown from two points of view in Fig. 10. On the left the satellites are shown in orbit as viewed by an observer in space who rotates with the earth. In this set of coordinates, the satellites do not appear to be in their orbital planes. In the right hand view the same series of satellites for an inertially-fixed observer are seen to be in inclined elliptical orbits. A ground trace and resulting coverage of a four satellite constellation are shown in Fig. 11, and a coverage diagram of a 15-satellite near-global system is shown in Fig. 12.

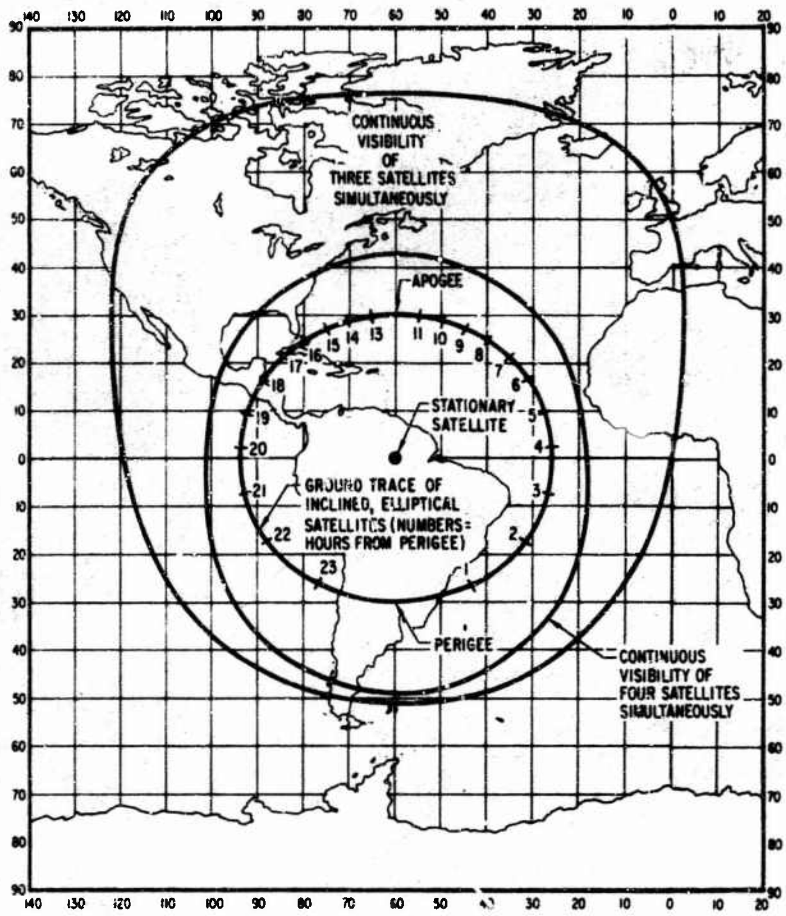

Fig. 11. Continuous Coverage Contours and Satellite Ground Trace for a Four Satellite Constellation

FREQUENCY AND MODULATION

Selection of a suitable carrier frequency and modulation method is essential for obtaining high navigation accuracy. It has been assumed that directional antennas will be unacceptable to many potential users. Consequently, a zero db gain user antenna is desired. Carrier frequencies in the range of 1 to 3 GHz seem ideal for this class of navigation system. At higher carrier frequencies, the signal energy intercepted by the user antenna diminishes and the required satellite power grows excessive. At lower carrier

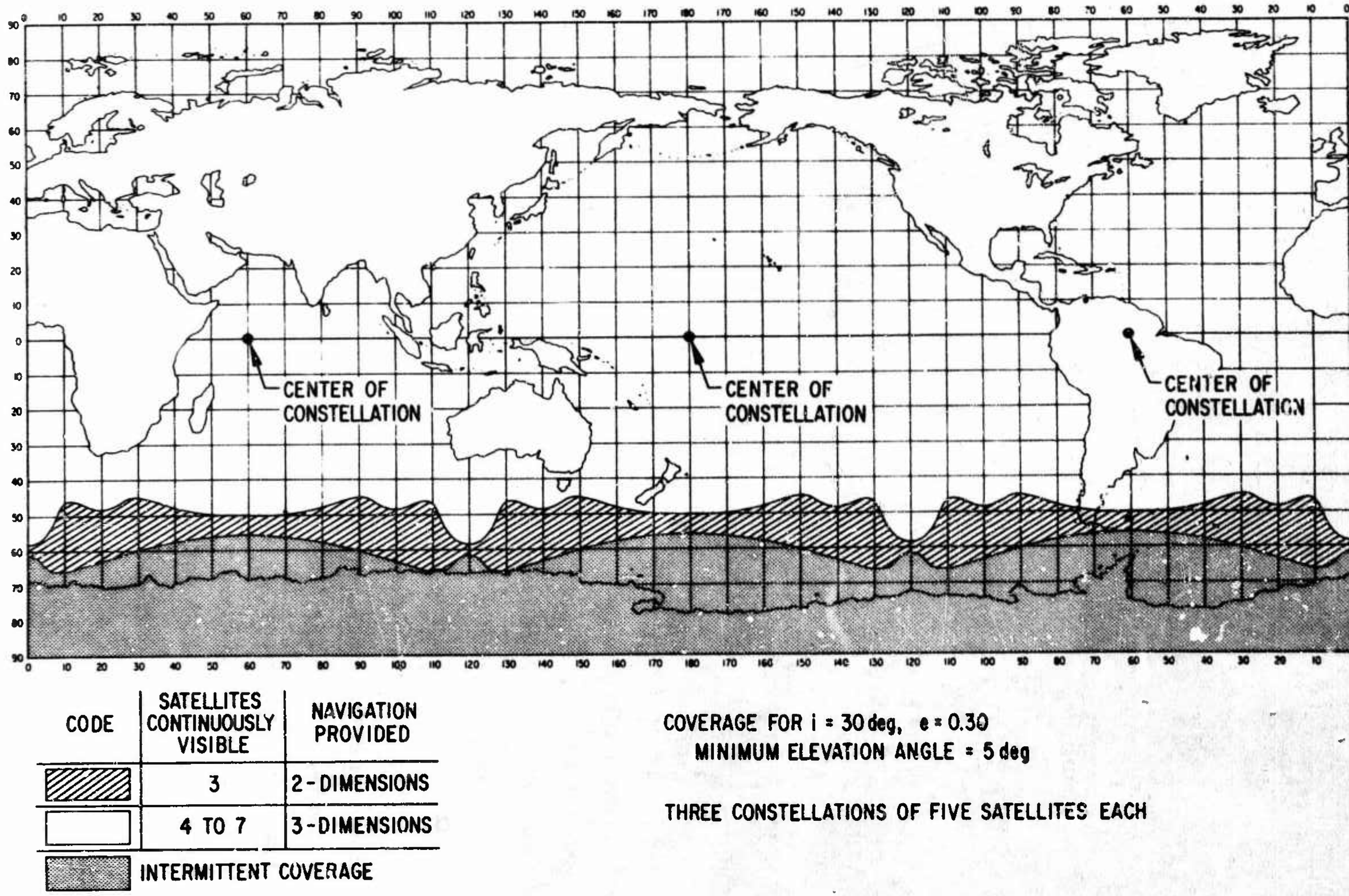

Fig. 12. Coverage for Fifteen Deployed Satellites

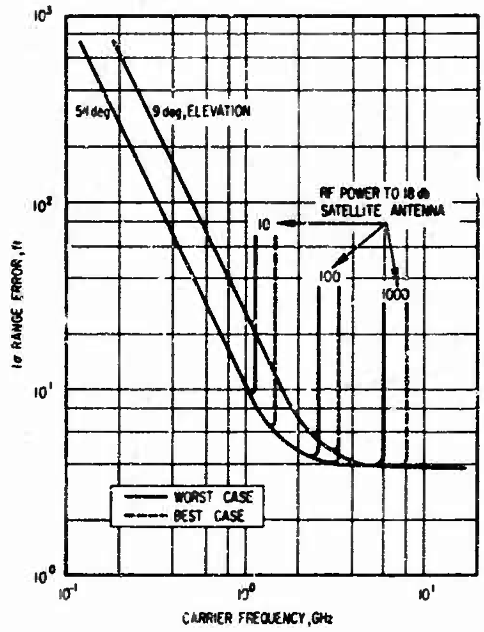

Fig. 13. Ranging Error as a Function of Satellite Transmitter Power and Frequency

frequencies ionospheric uncertainties contribute to an unacceptable error. These effects for several satellite RF powers are shown in Fig. 13. Two lines for each power level are shown representing a range of receiver noise temperature and antenna gains corresponding to the worst and best case expected. The vertical asymptotes signify an inability of the receiver to maintain lock under user acceleration. The accuracy shown is 1σ accuracy of a single range measurement and is reflected as a net navigation error two to three times as large.

The measurement accuracy objectives and the ability to resolve range ambiguities establish the basic requirements for signal power and bandwidth. The signal must allow very efficient reception techniques to be employed with the low signal levels encountered in satellite systems together with an inherent ability to reject interfering signals and multipath effects. A continuous signal phase modulated by a pseudo-random sequence has most of these characteristics.

USER EQUIPMENT

Receivers capable of simultaneously demodulating four separate satellite transmissions are required for continuous position fixing. A single RF amplifier can be used and the orthogonality of the pseudo noise sequence is sufficient to separate the signals if they will occupy the same segment of the spectrum. In addition, a computer of modest capability is required to reduce the measurements to geodetic coordinates. Essentially the same equipment can extract the frequency shift of the incoming signals and thereby allow the computation of the user's velocity vector with high precision. Somewhat simpler, and consequently less expensive, equipments are adaptable to the user who is not moving and, therefore, does not require simultaneous measurements. In addition, a less expensive class of user equipment is possible in which the time measurements are relayed to a central computer for reduction to geodetic coordinates.

GROUND SUPPORT EQUIPMENT

Each satellite constellation requires ground stations to establish satellite positions, make ionospheric corrections on the data, supply the information to be transmitted to the user in a suitable format, and ensure time synchronization of the satellite signals. The equipment might be envisioned as a 15-ft tracking antenna and two vans (including a general purpose computer) at one location and two to four sets of auxiliary ground stations, each in one van with a 5-ft non-tracking antenna. Suitable selection of sites for these stations will allow considerable control of the detailed error performance of the system. Use can be made of the near-zero error performance of the system within a few hundred miles of any station to adjust system performance to detailed user needs.

CONCLUSION

A type of navigation satellite system has been described which will allow nearly ideal navigation performance using presently developed technology.

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